Burning Plasma

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In burning plasma, the energy released from fusion reactions is responsible for self-heating the plasma, allowing for an environment where fusion reactions can further occur with less dependence on external heating sources. To achieve this, plasma is magnetically confined inside a fusion reactor, such as a tokamak, and deuterium and tritium fuel is injected into the plasma to start the fusion process. The fuel is injected by a process called Neutral Beam Injection (NBI), which also is a form of external heat being applied to the plasma. This increase in heating causes the plasma to be at temperatures of 10-20 keV, where deuterium and tritium can fuse. Particle motion also plays an important role in understanding the inner workings of a tokamak and what leads to fusion conditions.

I. INTRODUCTION: HISTORY & PROGRESS

Nuclear energy has been used around the world for countless years in the form of fission – the process of splitting a large nucleus into smaller nuclei. Along with other sources of energy, such as fossil fuels and natural gas, the world population has been able to sustain its power needs through these methods. These methods however contribute a large portion of pollution to the planet that is not sustainable for future generation. An alternative method to generating energy is through nuclear fusion. Not only is there no harmful by products, compared to splitting radioactive atoms or burning fossil fuels, but we are also able to produce more energy to meet the needs of the people. The net energy generated from a fusion reactor can be as much as four times the amount compared to nuclear fission[1].

The most promising design to date to achieve a sustained nuclear fusion reactor is through a tokamak. A tokamak is a torus-shaped confinement chamber where magnetic fields are used to confine plasma. The tokamak was first designed in 1951 by Soviet physicist Andrei Sakharov and Igor Tamm[1]. However, a tokamak is not the only design that is being used to date to confine plasma in the hopes of achieving a self-sustaining fusion reactor. In the same year, Lyman Spitzer worked on another fusion reactor called a stellarator at the Princeton Plasma Physics Laboratory[1]. A stellarator is similar to a tokamak style reactor except its configurations is a twisted helix structure. Since the magnetic fields that confine the plasma in this structure differ from a tokamak, the result is that there is no need for a toroidal current to be induced into the plasma[1]. Because of this, plasma stability can be greater. However, due to the complex design and computer modeling necessary for stellarators to operate, a tokamak style reactor is the main focus for future burning plasma experiments currently.

Current progress in the Tokamak Fusion Test Reactor (US) and the Joint European Torus (UK) have shown fusion power output of 10MW or more for less than a second. The heat supplied from fusion reactions consisted of less than 13% of the overall heat supplied to the plasma[2]. Future developments are focused around ITER, the International Thermonuclear Experimental Reactor, where over 50% of the heat supplied will come from fusion reactions and produce about 500MW of energy over a time span of 300 seconds[2]. ITER will be a largest tokamak built to date with a vessel size of 19 meters in diameter and 11 meters in height. The goal of ITER is not to generate electricity for the general public, but to show that a positive gain of energy can be acquired through a sustained fusion reaction[1].

The inner workings of operating a fusion reactor can be complex and hard to understand. To break down how burning plasma is achieved, a conceptual/mathematical descriptions of how plasma is confined and moves inside the tokamak will be presented. Following this, how fuel is injected into the tokamak for fusion to occur will be presented as well. The process of fuel inject is less complicated compared to some of the other topics encountered in the study of burning plasma, however the effects of the fuel being injected give rise to more complicated motions inside the tokamak.

Throughout the years of fusion research, many experiments and observations were done to see how sustained fusion can be achieved. The necessary conditions that we aim for have to fall under the Lawson Criterion, which tells us the minimum of specific parameters we have to have in order for our burning plasma to produce as much energy as it uses. Finally, a description of the power generated from the fusion reactions will be shown. This includes the power generated from the fusion reactions as well as the power loss through bremsstrahlung radiation. Bremsstrahlung radiation is how heat is dissipated from the confined particles inside of the tokamak chamber[3].

II. BURNING PLASMA

Burning plasma is when at least 50% of the total heating power comes from the fusion reactions that will take place in the plasma chamber. We represent this with a ration of f_α given by[4],

$$f_\alpha = \frac{P_\alpha}{P_{ext} + P_\alpha}. \tag{1}$$

Here P_α represents the energy that the alpha particle carries from the fusion reaction and P_{ext} represents the external heating power that will be used to heat up the plasma to the required temperatures.

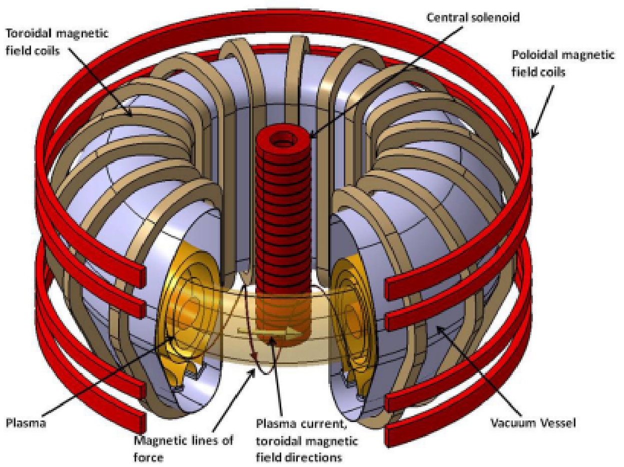

FIG. 1. The image above shows the central solenoid, toroidal magnetic field coils, and poloidal magnetic field coils used to drive the plasma current and confine the plasma inside the tokamak. (taken from ref. [3])

How well a fusion reactor operates is measured by a Q factor given by,

$$Q = \frac{P_\alpha + P_{neutron}}{P_{ext}} = \frac{P_{output}}{P_{input}}, \tag{2}$$

where $P_{neutron}$ is the power carried from the neutron in the fusion reaction. In comparison to how much energy is carried by the alpha particle, the neutron carries roughly 80% of the total energy produced from one reaction[3]. Currently with a deuterium and tritium reaction, this neutron particle will interact with a blanket outside of the tokamak, causing this blanket to heat up[3]. Electricity will be produced this way until more favorable reaction can be shown to be feasible, such as a hydrogen-hydrogen fusion reactions. Electricity from these reactions will come from the bremsstrahlung radiation that is produced from these high energy particles interacting with the magnetic and electric fields.

III. TOKAMAK DESIGN AND CONFIGURATION

There are many different types of fusion reactors that are currently being used around the world to test and generate burning plasma experiments. A diagram of a tokamak style fusion reactor is shown in Figure 1. A tokamak is an axisymmetric toroidal plasma confinement device[4]. The main systems that allow for burning plasma experiments are the magnetic field coils, external heating and current drive, and the divertor system[4]. These main components allow plasma to be contained from touching any of the surfaces in the tokamak vessel, while driving the plasma around the tokamak. The divertor system is mainly used for transporting impurities out of the plasma to help maintain the pressure and temperature for fusion.

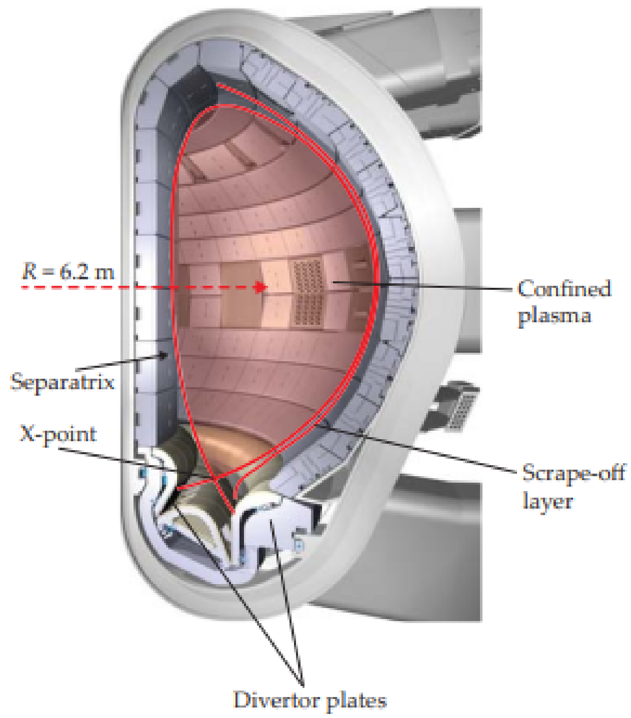

FIG. 2. Here we can see a cross section of the tokamak chamber where the red line depicts the polodial magnetic field line. These polodial fields form closed and open loops where plasma is separated into core plasma and edge plasma (also known as the scrape-off layer). The last closed loop of the magnetic field lines is known as the separatrix. (taken from ref. [2])

The plasma is magnetically confined to the tokamak chamber through a combination of toroidal and poloidal magnetic fields. The resulting magnetic field is then a helical shaped shown by the black arrow line in Figure 1. The dominant magnetic field of the system comes from the toroidal magnetic coils that wraps around the short way of the tokamak chamber. By running a current through these coils, a toroidal magnetic field is created which help confine charged particle to these magnetic field lines. This helps maintain the stability of the plasma and provided partial confinement against the outward radial expansion forces that the charge particles experience[4]. The magnetic field can be calculated by using Amperes Law.

The poloidal magnetic field is generated through coils that circulate around the entire tokamak. The central solenoid also creates a poloidal magnetic field, however, its main purpose is to induce a change in flux that creates a toroidal electric field to help drive the plasma current[5].

To understand these magnetic fields better we can start from Ampere's Law again written as[6]

$$\nabla \times \vec{B} = \mu_o \vec{J}, \tag{3}$$

where μ_o is the permeability of free space and J is the current density being passed through the wire. Integrating over a surface $\vec{S}$[6],

$$\int (\nabla \times \vec{B}) \cdot d\vec{S} = \int \mu_o \vec{J} \cdot d\vec{S}. \tag{4}$$

Stokes theorem allows us to rewrite this surface integral into a line integral of a closed loop in the form of[6]

$$\oint \vec{B} \cdot d\vec{l} = \int \mu_o \vec{J} \cdot d\vec{S}. \tag{5}$$

$$B_\phi(R) = \frac{\mu_o I}{2\pi R}, \tag{6}$$

which then gives back our toroidal magnetic field in the radial direction with respect to R, where I is the current running through the magnetic field coils

As stated before, the magnetic field generated from the central solenoid induces a toroidal electric field according to Faraday's law[6],

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}. \tag{7}$$

These electric and magnetic fields allow for a stable plasma confinement, however they also generate complex particle motions that will be discussed in a Section V..

IV. PLASMA GENERATION AND TOKAMAK START UP

The way plasma is generated inside of the tokamak chamber by ionizing gas through electron collisions. First the tokamak chamber has to have all of the air sucked out of it, making it a vacuum chamber. This allows for the amount of impurities to be at a minimum, which would effect the overall plasma operation. Generally, some free electrons will be present once the gas is injected in, if not then they can be supplemented through radiation[5]. These few electrons are accelerated and confined by the electric and magnetic fields of the tokamak. Once the electron gathers enough energy, $13.6eV$, then it has a chance of knocking an electron off of the neutron gas atom[5]. This process of ionization is repeated over as more electrons are detached from the neutron atom. The end product is a mostly quasi-neutral plasma that can reach temperature of roughly 1-2 keV or 10-20 million degrees kelvin[4].

V. PARTICLE MOTION

The way electrons and positive ions move around inside of the tokamak can generate complex behaviors of particle motion. These complex behaviors are very important in our understanding of fusion research because they play an important role in actually confining the charge particles through the magnetic fields. A short and simple descriptions of how particles move inside the tokamak are presented, however, there are more complex topics regarding particle motion that are not talked about.

Particles in the presence of magnetic and electric fields will experience a a force known as the Lorenz force, which is given by[7]

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}), \tag{8}$$

where q is the charge of the particle, $\vec{v}$ is the velocity of the particle and $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields the particle is subjected to.

Let's look at a particle motion in the presence of only a magnetic field, so set $\vec{E} = 0$. To simplify the motion even more, we can assume that the direction the particle is moving is perpendicular to a magnetic field that points away from the reader, a magnetic field in the direction that is depicted in Figure 3. This will make ions, that are positively charged, move in a circular motion with an initial direction upward relative to where the particle entered the magnetic field. For electrons, we get a similar motion except they will be directed downward relative to where they entered the magnetic field.

Now to look at a more realistic approach, we now consider that the particles direction is not perpendicular to the direction of the magnetic field. With this change, the particle will now gyrate around the magnetic field lines as shown in Figure 4 and Figure 5. The direction in which they gyrate is given by the charge of the particle.

If we rewrite our Lorenz force equation into the form of[7]

$$m\frac{dv}{dt} = q(\vec{E} + \vec{v} \times \vec{B}), \tag{9}$$

where m is the mass of the particle, we can see that ions and electrons will gyrate differently because of their difference in mass. The radius at which these particles gyrate relative to the magnetic field line they are gyrating around is known as the Larmor radius given by[7]

$$r_L = \frac{mv_\perp}{|q|B}, \tag{10}$$

where r_L is the Larmor radius, $v_\perp$ is the perpendicular velocity component, and B is the magntiude of the magnetic field.

Because the force on the particle is dependent on their charge, positive ions will initially be directed upwards while negative particle are directed downward in the tokamak chamber. Looking at Figure 3, we can see how the upward and downward motion of the particle induce a charge separation in the plasma. This charge separation creates an electric field in the downward direction, which then effects the particle's motion in the tokamak chamber[6]. There would be an overall drift, radial outward from the center of the tokamak. However, the combination of the toroidal and polodial fields causes the particles to be redirected away from the walls of the tokamak chamber.

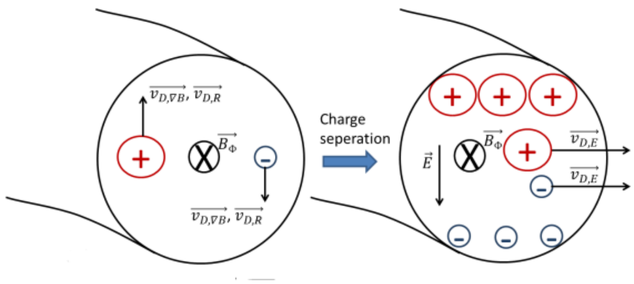

FIG. 3. Here we can see a cross section of the tokamak chamber where the red line depicts the polodial magnetic field line. These polodial fields form closed and open loops where plasma is separted into core plasma and edge plasma (also known as the scrape-off layer). The last closed loop of the magnetic field lines is known as the separatrix. (taken from ref. [6])

FIG. 4. Here we can see the gyration of an ion when it is bound to a magnetic field line. (taken from ref. [7])

VI. NEUTRAL BEAM INJECTION

Neutral beam injection, NBI, is mainly used as an external heat source for the tokamak, while delivering the necessary fuel that will be used for the fusion reactions[3]. Other external heating methods can be used and are used for varying fusion reactors. ITER plans to use three different external heating sources which are NBI, ion cyclotron heating, and electron cyclotron heating. The external heating source that will be focused on in this paper is NBI, mainly a conceptual description of the operation of this system.

Neutral beam injection is when neutral atoms of 40 keV to 1 MeV[3] in energy are injected into the plasma causing the overall temperature of the plasma to rise to the range of 10-20 keV, from the initial ohmic heating of 1-2 keV[4]. This rise in temperature is what is necessary to give the ions enough thermal energy to fuse in the plasma. This temperature is also the necessary temperature that matches the Lawson Criteria, which will be discussed in a later section.

The neutral beam injection process starts off with the production of negative ions of hydrogen or deuterium-tritium, depending on what type of burning plasma experiment is being done. This negative ions production can either be described as surface production or volume production. In surface production low work function materials are used to produce the excess electrons in order to make our neutral atoms into negative ions[8]. The material that is used for surface production is cesium because cesium has the lowest work function.

Volume production is when we create negative ions through dissociative electron attachment[8]. By creating highly excited ro-vibrational molecules of hydrogen, we can then have it col-

FIG. 5. Here we can see the gyration of an electron when it is bound to a magnetic field line. (taken from ref. [7])

lide with a slow moving (about 1eV) electron causing the production of a negative hydrogen ion and a neutral hydrogen atom[8]. This additional electron is weakly bounded to the hydrogen atom, in comparison to an electron bounded to a neutral hydrogen atom. This weak binding allows the neutralization of this ion to be easier, however, the electron could also be knocked off by particle collisions during the process causing the loss of a negative ion.

The neutralization of these atoms can be done differently with three methods being gas neutralization, plasma neutralization, and photondetachment neutralization. Gas neutralization was the first to be used with an efficiency of about 60%, plasma neutralization gives about an 80% efficiency, and photondetachment has an almost perfect efficiency[9]. The last two that were listed require additional systems that take up more energy. The gas neutralization method focuses on colliding the negative ion with a neutral atom causing the production of a neutral gas molecule and free electron. These fast moving molecules are then injected into the plasma, where they are ionized and transfer their energy to raise the plasma temperature to the require degree.

VII. ACHIEVING FUSION

In order for hydrogen ions to fuse into a helium ion, they must first overcome the Coulomb repulsion force. In the sun, atoms are able to fuse at roughly 15 million degrees Kelvin because the immense gravitation pressure can force the atoms to come close enough that the strong nuclear force takes over, beating the Coulomb force[10].

A more classical way to think about fusing atoms is by forcing them to collide with one another, at high velocities where they can exert enough force to overcome the Coulomb force. However, if we think classically about this, the thermal energy required to force these atoms collide comes out to be on the order of several billions of degrees Kelvin[10]. The solution to this comes from understanding some quantum mechanics. The two hydrogen ions have a probability of fusion by tunneling through this potential barrier and the more thermal energy we give the atoms, the more likely they are to tunnel through this barrier[10]. Solving for the thermal energy required for two atoms to fuse now comes to around 100 million degrees Kelvin.

Deuterium and tritium will fuse together in the neighborhood of 100 million degrees Kelvin or 10 keV. The necessary energy that is required to maintain the plasma at this temperature comes from understanding the power balance between heat loss through bremsstrahlung radiation and the heat supplied through alpha particle interactions and external heat supplied. This power balance has to satisfy a criteria known as the Lawson Criterion[3].

For a fusion reaction between Deuterium and Tritium at a temperature of about 15 keV, the Lawson Criterion is given by[3]

$$n_e \tau_e = 10^{20} sm^{-3}, \tag{11}$$

where n_e is the density of the plasma and τ_e is the energy confinement time. The energy confinment time tells us the rate at which heat is loss due mainly to bremsstrahlung radiation. In order for a fusion reactor to have a Q value of 1, so a break even value, this condition has to be met.

Following this, if we want to consider a range of temperatures in which this condition can be met, we can include a temperature term. What we are really looking at is the fusion reaction rate $<\sigma v>$, which varies squarely with the temperature of the plasma[3]. This gives the following Lawson Criterion, also known as the Triple Product of[3],

$$n_e T_e \tau_e > 1.5 \times 10^{21} keV sm^{-3}, \tag{12}$$

where again we are considering deuterium and tritium fusing at around 15 keV.

VIII. POWER GENERATION

The power generated from alpha particle being produced from fusion reactions can be given by[3],

$$P_\alpha = n_e n_t <\sigma v> E_\alpha V_p, \tag{13}$$

where n_e and n_t are the densities of the deuterium and tritium atoms, $<\sigma v>$ is the reaction rate for a D-T reaction, E_α is the energy carried by one alpha particle (3.5 MeV) and V_p is the plasma volume. Since we will be working with a 50/50 mix of deuterium and tritium in our reactor the densities can be combined to be n^2. The reaction rate will vary with the temperature squared. By making these substitutions and forgoing constants, we can rearrange our equation to be

$$\frac{P_\alpha}{V_p} \propto p^2, \tag{14}$$

where p is the plasma pressure. We see that the power per unit volume is proportional to the plasma pressure squared[2]. This means if we can double our plasma pressure, the power will be 4 times as great. Plasma pressure is one of the key components in achieving the necessary power output for a break even burning plasma reactor. If the plasma pressure is not high enough, then we wont be able to produce sufficient amount of energy. On the other hand, if the plasma pressure is too great, then there is a chance of the magnetic confinement failing, causing damage to the surrounding structure.

IX. CONCLUSION

In summary, we have looked at several different aspects governing the burning plasma process. Burning plasma is when over 50% of the heat needed to sustain the plasma temperature comes from the fusion reactions that will take place in the plasma volume. The heating from these reactions comes from the alpha particle interacting with the surrounding plasma, causing the plasma to gain energy and the alpha particle to lose energy. Plasma must first be confined in a device, such as a tokamak, where magnetic and electric fields are used to keep plasma confined to a region where it does not interact with surrounding material. With magnetic confinement, a comprehensive study of particle motion inside of the plasma chamber is needed to fully understand all of the interactions happening inside of the plasma.

To turn this plasma into burning plasma, the temperatures need to be within the range of 10-20 keV or upwards of 100 million degrees Kelvin. At these temperatures, the fusion fuel (deuterium and tritium) will fuse upon collision releasing an alpha particle and neutron as a result. To get to these temperature, several external heating methods are used with neutral beam injection playing one of the most important roles. Through this method deuterium and tritium ions are accelerated to very high speeds resulting in a thermal energy of several times that of the current plasma. Once these gas molecules are injected, the overall plasma volume is heated to temperature of 10-20 keV. Along with the external heating and heating power supplied by the alpha particle, the plasma is kept at this temperature until the fuel is exhausted.

Future developments of burning plasma experiments and nuclear fusion reactors are currently center around ITER, with many different countries pulling resources into the project. ITER has several goals, one being a 500 MW power output from a 50 MW external heat applied. This would give ITER a Q=10, which is ten times the break-even condition. Deuterium-Tritium experiments are expected to begin with ITER in 2035, with DEMO being starting its construction in 2040. DEMO will be the first power plant to be built that will be possible of generating electricity[1].

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